B_s mixing: gate to new physics?

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B physics

Strategies to explore the TeV scale:

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High energy:
direct production of new particles
Tevatron, LHC

High precision:
quantum effects from new particles
high statistics

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B physics

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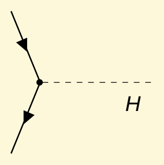
With precision measurements one studies the couplings and mixing patterns of the new particles which the LHC will discover.

Yukawa sector

Yukawa coupling of the Higgs field:

$$y_{ij}\bar{f}_i f_j (v + H)$$



$\Rightarrow$ quark mass matrix: $m_{ij} = y_{ij} v$

diagonalisation $\Rightarrow$ fermion masses and CKM matrix V_{CKM}.

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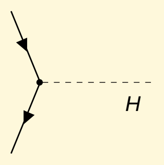

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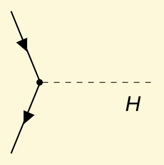

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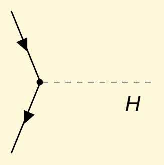

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y_{ij}, V_{CKM} complex $\Rightarrow$ CP violation

10 parameters in the quark sektor,
10 or 12 parameters in the lepton sector.

Expand the CKM matrix V in $V_{us} \simeq \lambda = 0.2246$:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3\left(1+\frac{\lambda^2}{2}\right)(\overline{\rho}-i\overline{\eta}) \\ -\lambda-iA^2\lambda^5\overline{\eta} & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\overline{\rho}-i\overline{\eta}) & -A\lambda^2-iA\lambda^4\overline{\eta} & 1 \end{pmatrix}$$

with the Wolfenstein parameters λ, A, $\overline{\rho}$, $\overline{\eta}$

CP violation $\Leftrightarrow \overline{\eta} \neq 0$

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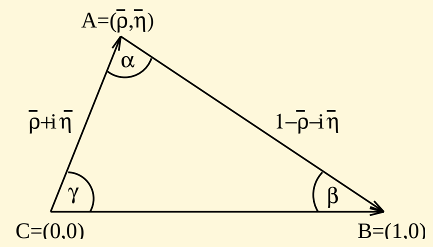
with the Wolfenstein parameters λ, A, $\overline{\rho}$, $\overline{\eta}$

CP violation $\Leftrightarrow \overline{\eta} \neq 0$

Unitarity triangle:

Exact definition:

$$\overline{\rho} + i\overline{\eta} = -\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} = \left|\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right| e^{i\gamma}$$



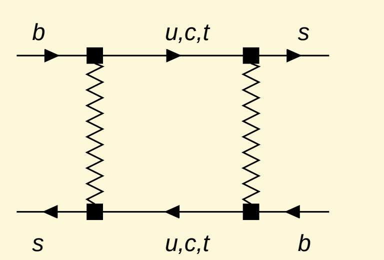
If new physics is associated with the scale Λ, effects on weak processes (such as weak B decays) are generically suppressed by a factor of order M_W^2/Λ^2 compared to the Standard Model.

$\Rightarrow$ study processes which are suppressed in the Standard Model.

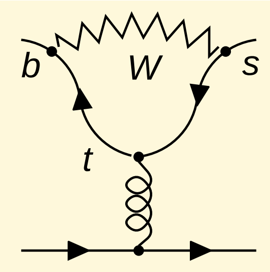
Especially sensitive to new physics are processes, in which (only) the Standard Model contribution is suppressed.

$\Rightarrow$ flavour-changing neutral current (FCNCs) processes

Examples for FCNC processes:



$B_s - \overline{B}_s$ mixing



penguin diagrams

$B_s - \overline{B}_s$ mixing basics

Schrödinger equation:

$$i \frac{d}{dt} \begin{pmatrix} |B_s(t)\rangle \\ |\overline{B}_s(t)\rangle \end{pmatrix} = \left(M - i\,\frac{\Gamma}{2} \right) \begin{pmatrix} |B_s(t)\rangle \\ |\overline{B}_s(t)\rangle \end{pmatrix}$$

where $B_s \sim \overline{b}s$ and $\overline{B}_s \sim b\overline{s}$.

$B_s - \overline{B}_s$ mixing basics

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3 physical quantities in $B_s - \overline{B}_s$ mixing:

$$\left|M_{12}^s\right|, \quad \left|\Gamma_{12}^s\right|, \quad \phi_s \equiv \arg\left(-\frac{M_{12}^s}{\Gamma_{12}^s}\right)$$

Two mass eigenstates:

$$\begin{aligned} \text{Lighter eigenstate:} \quad |B_L\rangle &= p|B_s\rangle + q|\overline{B}_s\rangle. \\ \text{Heavier eigenstate:} \quad |B_H\rangle &= p|B_s\rangle - q|\overline{B}_s\rangle \end{aligned}$$

with masses $M_{L,H}$ and widths $\Gamma_{L,H}$.
Further $|p|^2 + |q|^2 = 1$.

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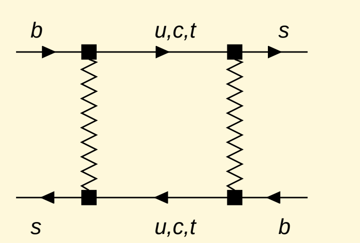
Relation of Δm_s and $\Delta\Gamma_s$ to $|M_{12}^s|$, $|\Gamma_{12}^s|$ and ϕ_s:

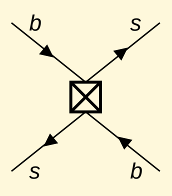
$$\begin{aligned} \Delta m_s &= M_H - M_L \simeq 2|M_{12}^s|, \\ \Delta\Gamma_s &= \Gamma_L - \Gamma_H \simeq 2|\Gamma_{12}^s| \cos\phi_s \end{aligned}$$

M_{12}^s stems from the dispersive (real) part of the box diagram, internal $(\bar{t}, t)$.
Γ_{12}^s stems from the absorpive (imaginary) part of the box diagram, internal $(\bar{c}, c)$.
(u's are negligible).



Theoretical uncertainty of M_{12}^s dominated by matrix element:

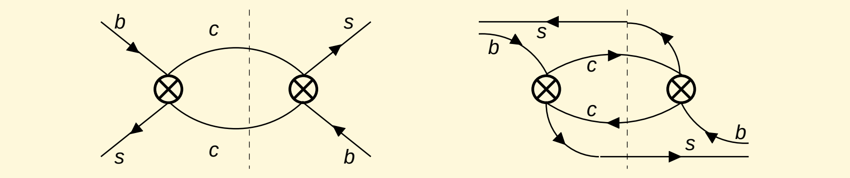
$$\langle B_s|\bar{s}_L\gamma_\nu b_L\,\bar{s}_L\gamma^\nu b_L|\bar{B}_s\rangle \quad = \quad \frac{2}{3} m_{B_s}^2\, f_{B_s}^2\, B$$



Optical theorem:

$$\Gamma_{12}^{s} \;=\; -\frac{1}{2M_{B_s}}\,\mathrm{Abs}\,\langle B_s|\, i\int d^4x\; T\,\mathcal{H}^{\Delta B=1}(x)\mathcal{H}^{\Delta B=1}(0)|\bar{B}_s\rangle$$

from final states common to B_s and $\overline{B}_s$.



Crosses: effective $|\Delta B| = 1$ operators from W-mediated b-decay

Γ_{12}^{s} is a CKM-favored tree-level effect associated with final states containing a $(\overline{c}, c)$ pair.

CP asymmetry in flavour-specific decays (semileptonic CP asymmetry):

$$a_{\rm fs}^s = \frac{\Gamma(\overline{B}_s(t) \to f) - \Gamma(B_s(t) \to \overline{f})}{\Gamma(\overline{B}_s(t) \to f) + \Gamma(B_s(t) \to \overline{f})}$$

with e.g. $f = X\ell^+\nu_\ell$. Untagged rate:

$$A_{\rm fs,unt}^s \equiv \frac{\int_0^\infty dt \left[\Gamma(\overset{(-)}{B_s} \to \mu^+ X) - \Gamma(\overset{(-)}{B_s} \to \mu^- X)\right]}{\int_0^\infty dt \left[\Gamma(\overset{(-)}{B_s} \to \mu^+ X) + \Gamma(\overset{(-)}{B_s} \to \mu^- X)\right]} \simeq \frac{a_{\rm fs}^s}{2}$$

Dilepton events:

Compare the number N_{++} of decays $(B_s(t), \overline{B}_s(t)) \to (f, f)$ with the number N_{--} of decays to $(\overline{f}, \overline{f})$.

Then $a_{\mathrm{fs}}^{s} = \dfrac{N_{++} - N_{--}}{N_{++} + N_{--}}$.

May 15, 2010: DØ presents

$$A_{\rm sl}^b = (-9.57 \pm 2.51 \pm 1.46) \cdot 10^{-3}$$

for a mixture of B_d and B_s mesons with

$$A_{\rm sl}^b = (0.506 \pm 0.043) a_{\rm sl}^d + (0.494 \pm 0.043) a_{\rm sl}^s$$

The result is 3.2σ away from $A_{\rm sl}^{b,\rm SM} = \left(-0.23^{+0.05}_{-0.06}\right) \cdot 10^{-3}$.

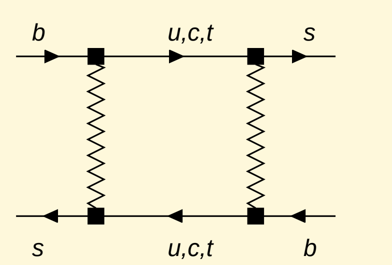
A. Lenz, UN, 2006

$B_s - \overline{B}_s$ mixing and new physics

Standard Model:

M_{12}^s from dispersive part of box, only internal t relevant;

Γ_{12}^s from absorptive part of box, only internal u, c contribute.



New physics can barely affect Γ_{12}^s, which stems from tree-level decays.

M_{12}^s is very sensitive to virtual effects of new heavy particles.

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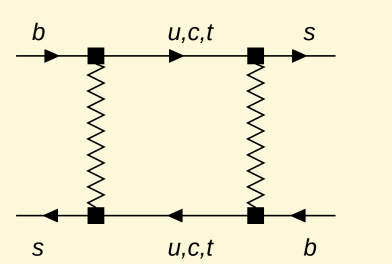

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$\Rightarrow$ $\Delta m_s \simeq 2|M_{12}^s|$ can change.

and in $\phi_s \simeq \arg(-M_{12}^s/\Gamma_{12}^s)$ the GIM suppression of ϕ_s can be lifted.

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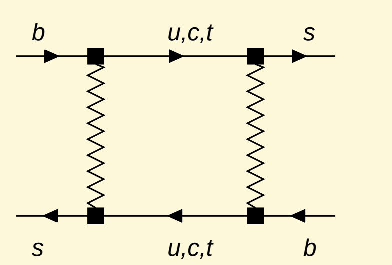

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$\Rightarrow$ $|\Delta\Gamma_s| = \Delta\Gamma_{s,\mathrm{SM}}\,|\cos\phi_s|$ is depleted and $|a_{\mathrm{fs}}^s|$ is enhanced, by up to a factor of 200.

To identify or constrain new physics one wants to measure both the magnitude and phase of M_{12}^s.

$$\rightarrow \qquad \Delta m_s = 2|M_{12}^s|$$

Three untagged measurements are sensitive to $\arg M_{12}^s$:

1. $|\Delta\Gamma_s| = 2|\Gamma_{12}^s|\,|\cos\phi_s|$
2. $a_{\rm fs}^s = \left|\frac{\Gamma_{12}^s}{M_{12}^s}\right| \sin\phi_s$
3. the angular distribution of $\overset{(-)}{B}_s \rightarrow VV'$, where V, V' are vector bosons.

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Gold-plated tagged measurement of $\arg M_{12}^s$:

Mixing-induced CP asymmetry in $a_{\rm mix}^{\rm CP}(B_s \rightarrow J/\psi\phi)$ (with angular analysis)

Generic new physics

The phase $\phi_s = \arg(-M_{12}/\Gamma_{12})$ is negligibly small in the Standard Model:

$$\phi_s^{\rm SM} = 0.2^\circ.$$

Define the complex parameter Δ_s through

$$M_{12}^s \equiv M_{12}^{\rm SM,s} \cdot \Delta_s \,, \qquad \Delta_s \equiv |\Delta_s| e^{i\phi_s^\Delta} .$$

In the Standard Model $\Delta_s = 1$. Use $\phi_s = \phi_s^{\rm SM} + \phi_s^\Delta \simeq \phi_s^\Delta$.

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Frequently used alternative notation:

$$\Delta_s = r_s^2 \cdot e^{i\,2\theta_s}$$

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The CDF measurement

$$\Delta m_s = (17.77 \pm 0.10 \pm 0.07)\ \mathrm{ps}^{-1}$$

and $$f_{B_s}\sqrt{B} = (210 \pm 16)\ \mathrm{MeV} \qquad \text{lattice world av.}$$

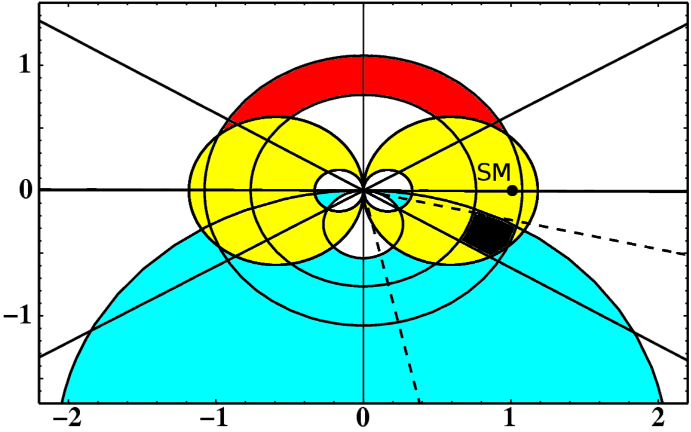
imply $$|\Delta_s| = 0.92 \pm 0.14_{\mathrm{(th)}} \pm 0.01_{\mathrm{(exp)}}$$

Status of December 2006: CDF or DØ data available for

- mass difference Δm_s,
- the semileptonic CP asymmetry a^s_{fs},
- the angular distribution in $\overset{(-)}{B}_s \to J/\psi\phi$ and
- $\Delta\Gamma_s$

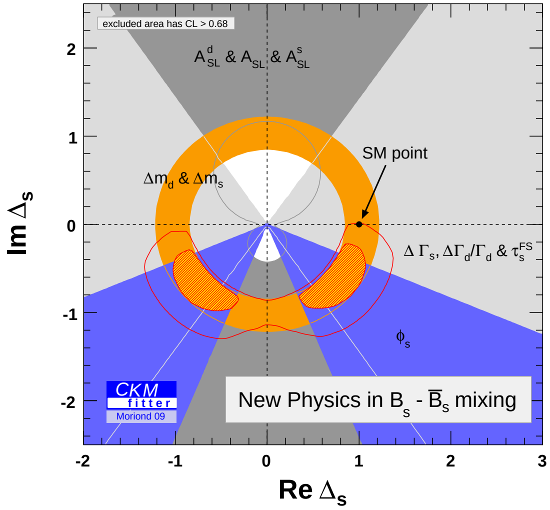
to constrain Δ_s.

The complex Δ_s plane in 2006:



We black area shown corresponds to a deviation from the Standard Model by 2σ. The area delimited by the dashed lines has mirror solutions in the other three quadrants. Alex Lenz, UN

The complex Δ_s plane before May 14, 2010:

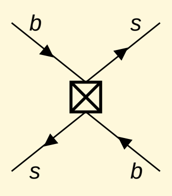


deviation driven by $A^{\mathrm{mix}}_{CP}(B_s \to J/\psi\phi)$ from CDF/DØ

Γ_{12} involves the two operators

$$\overline{s}_L \gamma_\nu b_L \, \overline{s}_L \gamma^\nu b_L \text{ and } \overline{s}_L^\alpha b_R^\beta \, \overline{s}_L^\beta b_R^\alpha$$

with matrix elements:



$$\begin{aligned}
\langle B_s | \overline{s}_L \gamma_\nu b_L \, \overline{s}_L \gamma^\nu b_L | \overline{B}_s \rangle &= \frac{2}{3} m_{B_s}^2 \, f_{B_s}^2 \, B \\
\langle B_s | \overline{s}_L^\alpha b_R^\beta \, \overline{s}_L^\beta b_R^\alpha | \overline{B}_s \rangle &= \frac{1}{12} \frac{m_{B_s}^4}{[m_b + m_s]^2} \, f_{B_s}^2 \, \widetilde{B}_S
\end{aligned}$$

Hadronic uncertainties are not an issue in

$$\left|\frac{\Gamma_{12}}{M_{12}^{\mathrm{SM}}}\right| = \left[32 \pm 8 + (17 \pm 2)\frac{\widetilde{B}_S}{B}\right] \cdot 10^{-3}$$
$$= (4.97 \pm 0.94) \cdot 10^{-3}$$

$$a_{\mathrm{fs}}^s = \frac{|\Gamma_{12}^s|}{|M_{12}^s|} \sin\phi_s = \frac{|\Gamma_{12}^s|}{|M_{12}^{\mathrm{SM,s}}|} \cdot \frac{\sin\phi_s}{|\Delta_s|} = (4.97 \pm 0.94) \cdot 10^{-3} \cdot \frac{\sin\phi_s}{|\Delta_s|}$$

If there is no new physics in a_{fs}^d, the DØ measurement of
$A_{\mathrm{sl}}^b = (-9.57 \pm 2.51 \pm 1.46) \cdot 10^{-3}$ roughly implies
$a_{\mathrm{fs}}^s = (-19 \pm 6) \cdot 10^{-3}$.

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If there is no new physics in $a_{\rm fs}^d$, the DØ measurement of $A_{\rm sl}^b = (-9.57 \pm 2.51 \pm 1.46) \cdot 10^{-3}$ roughly implies $a_{\rm fs}^s = (-19 \pm 6) \cdot 10^{-3}$.
To maximise $|a_{\rm fs}^s|$ choose the minimal value $|\Delta_s|_{\rm min} = 0.78$ to find

$$a_{\rm fs}^s \geq 7.6 \cdot 10^{-3} \sin\phi_s .$$

The DØ result therefore means

$$\sin\phi_s \leq -2.5 \pm 0.8.$$

It helps to put some new physics in $a_{\rm fs}^d$:

Measurement by B factories: $a_{\rm fs}^d = (-4.7 \pm 4.6) \cdot 10^{-3}$

However: $a_{\rm fs}^d$ can be better determined indirectly through

$$a_{\rm fs}^d = \frac{|\Gamma_{12}^d|}{|M_{12}^d|} \sin(\phi_d^{\rm SM} + \phi_d^{\Delta}) \qquad \text{with} \quad \phi_d^{\rm SM} = (-5 \pm 2)^\circ$$

using the measurements of $\Delta m_d = 2|M_{12}^d|$ and of $2\beta + \phi_d^{\Delta} = (21 \pm 1)^\circ$ from $A_{CP}^{\rm mix}(B_d \to J/\psi K_S)$.

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$\Rightarrow$ requires fit to unitarity triangle to find β

Other connection between B_d and B_s mixing:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \left| \frac{V_{ts}}{V_{td}} \right|^2 \xi^2 \frac{|\Delta_s|}{|\Delta_d|}$$

with

$$\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}} = 1.23 \pm 0.03$$

Global analysis of $B_s - \overline{B}_s$ mixing and $B_d - \overline{B}_d$ mixing

Based on work with A. Lenz and the CKMfitter Group (J. Charles, S. Descotes-Genon, A. Jantsch, C. Kaufhold, H. Lacker, S. Monteil, V. Niess)

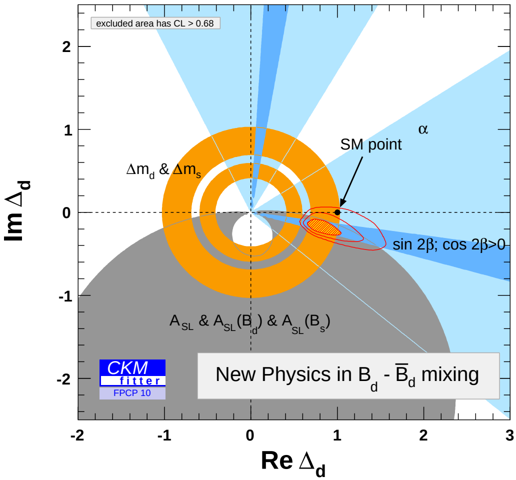
Rfit method: No statistical meaning is assigned to systematic errors and theoretical uncertainties.
We have performed a simultaneous fit to the Wolfenstein parameters and to the new physics parameters Δ_s and Δ_d in three scenarios.

Scenario I: arbitrary complex parameters Δ_s and Δ_d

Scenario II: new physics is minimally flavour violating (MFV) (meaning that all flavour violation stems from the Yukawa sector) and y_b is small:
one real parameter $\Delta = \Delta_s = \Delta_d$

Scenario III: MFV with a large y_b: one complex parameter $\Delta = \Delta_s = \Delta_d$

Results in scenario I:



Reason for the tension with the SM: $B(B^+ \to \tau^+ \nu_\tau)$

SM prediction (CL$= 2\sigma$):

$$B(B^+ \to \tau^+ \nu_\tau) = \left(0.763^{+0.214}_{-0.097}\right) \cdot 10^{-4}$$

Average of several measurements by BaBar and Belle:

$$B^{\rm exp}(B^+ \to \tau^+ \nu_\tau) = (1.68 \pm 0.31) \cdot 10^{-4}$$

Reason for the tension with the SM: $B(B^+ \to \tau^+ \nu_\tau)$

SM prediction (CL$= 2\sigma$):

$$B(B^+ \to \tau^+ \nu_\tau) = \left(0.763^{+0.214}_{-0.097}\right) \cdot 10^{-4}$$

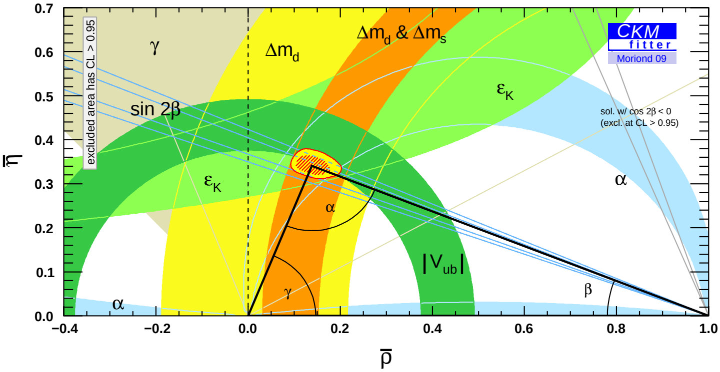
Average of several measurements by BaBar and Belle:

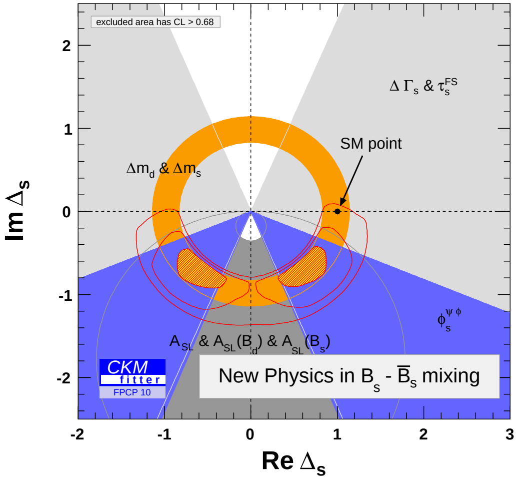
$$B^{\text{exp}}(B^+ \to \tau^+ \nu_\tau) = (1.68 \pm 0.31) \cdot 10^{-4}$$

$$B(B^+ \to \tau^+ \nu_\tau) = \frac{G_F^2 m_{B^+} m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_{B^+}^2}\right)^2 |V_{ub}|^2 f_B^2 \tau_{B^+}.$$

But with e.g. $f_B = 210\,\text{MeV}$ and $|V_{ub}| = 4.4 \cdot 10^{-3}$ find $B(B^+ \to \tau^+ \nu_\tau) = 1.51 \cdot 10^{-4}$. These parameters comply with the global fit to the UT only, if new physics changes the constraints from $A_{CP}^{\text{mix}}(B_d \to J/\psi K_S)$, Δm_d and $\Delta m_d/\Delta m_s$.

Global fit in the SM:





without 2010 CDF/DØ data on $B_s \to J/\psi\phi$

Other authors have seen a tension with the SM in the same direction stemming from ϵ_K.

Lunghi,Soni; Buras, Guadagnoli

In our fit the tension with ϵ_K is mild, because we use a more conservative error on the hadronic parameter $\widehat{B}_K = 0.724 \pm 0.004 \pm 0.067$ and because the Rfit method is more conservative.

p-values:

Calculate $\chi^2/N_{\rm dof}$ with and without a hypothesis to find:

Hypothesis	p-value
$\mathrm{Im}(\Delta_d) = 0$ (1D)	$2.5\,\sigma$
$\mathrm{Im}(\Delta_s) = 0$ (1D)	$3.1\,\sigma$
$\Delta_d = 1$ (2D)	$2.5\,\sigma$
$\Delta_s = 1$ (2D)	$2.7\,\sigma$
$\mathrm{Im}(\Delta_d) = \mathrm{Im}(\Delta_s) = 0$ (2D)	$3.8\,\sigma$
$\Delta_d = \Delta_s$ (2D)	$2.1\,\sigma$
$\Delta_d = \Delta_s = 1$ (4D)	$3.4\,\sigma$

Removing a_{fs}^{d} as an input the global fit predicts (at 2σ):

$$a_{\mathrm{fs}}^{d} = \left(-3.4^{+2.3}_{-1.2}\right) \cdot 10^{-3}.$$

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Same game with $a_{\mathrm{fs}} = (0.506 \pm 0.043) a_{\mathrm{sl}}^d + (0.494 \pm 0.043) a_{\mathrm{sl}}^s$:

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$$a_{\rm fs} = \left(-4.2^{+2.7}_{-2.6}\right) \cdot 10^{-3}.$$

This is just 1.5σ away from the DØ/CDF average

$$a_{\rm fs} = (-8.5 \pm 2.8) \cdot 10^{-3}.$$

The fit in scenario II (real $\Delta_s = \Delta_d$) is not better than the SM fit and gives $\Delta = 0.907^{+0.091}_{-0.067}$.

Scenario III (complex $\Delta_s = \Delta_d$) fits the data quite well irrespective of whether $B(B^+ \to \tau^+\nu_\tau)$ is included or not.

Hypothesis	p-value
$\mathrm{Im}(\Delta) = 0$ (1D)	$3.4\,\sigma$
$\Delta = 1$ (2D)	$3.1\,\sigma$

Supersymmetry

The MSSM has many new sources of flavour violation, all in the supersymmetry-breaking sector.

No problem to get big effects in $B_s - \overline{B}_s$ mixing, but rather to suppress the big effects elsewhere.

Squark mass matrix

Diagonalise the Yukawa matrices Y^u_{jk} and Y^d_{jk}

$\Rightarrow$ quark mass matrices are diagonal, super-CKM basis

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E.g. Down-squark mass matrix:

$$M^2_{\tilde d} = \begin{pmatrix}
\left(M^{\tilde d}_{1L}\right)^2 & \Delta^{\tilde d\,LL}_{12} & \Delta^{\tilde d\,LL}_{13} & \Delta^{\tilde d\,LR}_{11} & \Delta^{\tilde d\,LR}_{12} & \Delta^{\tilde d\,LR}_{13} \\
\Delta^{\tilde d\,LL}_{12}{}^{*} & \left(M^{\tilde d}_{2L}\right)^2 & \Delta^{\tilde d\,LL}_{23} & \Delta^{\tilde d\,RL}_{12}{}^{*} & \Delta^{\tilde d\,LR}_{22} & \Delta^{\tilde d\,LR}_{23} \\
\Delta^{\tilde d\,LL}_{13}{}^{*} & \Delta^{\tilde d\,LL}_{23}{}^{*} & \left(M^{\tilde d}_{3L}\right)^2 & \Delta^{\tilde d RL}_{13}{}^{*} & \Delta^{\tilde d\,RL*}_{23} & \Delta^{\tilde d\,LR}_{33} \\
\Delta^{\tilde d\,LR}_{11}{}^{*} & \Delta^{\tilde d RL}_{12} & \Delta^{\tilde d RL}_{13} & \left(M^{\tilde d}_{1R}\right)^2 & \Delta^{\tilde d\,RR}_{12} & \Delta^{\tilde d\,RR}_{13} \\
\Delta^{\tilde d\,LR}_{12}{}^{*} & \Delta^{\tilde d\,LR*}_{22} & \Delta^{\tilde d RL}_{23} & \Delta^{\tilde d\,RR}_{12}{}^{*} & \left(M^{\tilde d}_{2R}\right)^2 & \Delta^{\tilde d\,RR}_{23} \\
\Delta^{\tilde d\,LR}_{13}{}^{*} & \Delta^{\tilde d\,LR}_{23}{}^{*} & \Delta^{\tilde d\,LR}_{33}{}^{*} & \Delta^{\tilde d\,RR}_{13}{}^{*} & \Delta^{\tilde d\,RR}_{23}{}^{*} & \left(M^{\tilde d}_{3R}\right)^2
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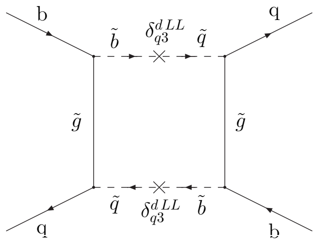
\Delta^{\tilde d\,LR\,*}_{12} & \Delta^{\tilde d\,LR\,*}_{22} & \Delta^{\tilde d\,RL}_{23} & \Delta^{\tilde d\,RR\,*}_{12} & \left(M^{\tilde d}_{2R}\right)^2 & \Delta^{\tilde d\,RR}_{23} \\
\Delta^{\tilde d\,LR\,*}_{13} & \Delta^{\tilde d\,LR\,*}_{23} & \Delta^{\tilde d\,LR\,*}_{33} & \Delta^{\tilde d\,RR\,*}_{13} & \Delta^{\tilde d\,RR\,*}_{23} & \left(M^{\tilde d}_{3R}\right)^2
\end{pmatrix}$$

Not diagonal! $\Rightarrow$ new FCNC transitions.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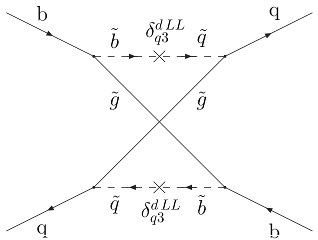
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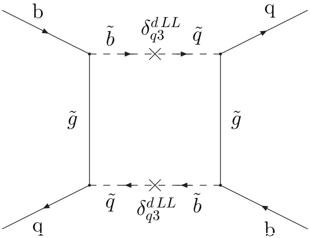
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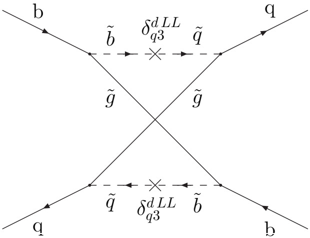
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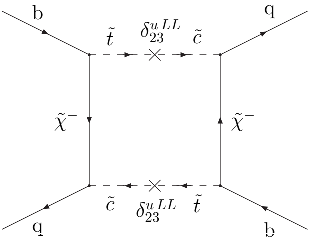
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Flavour and SUSY GUTs

Linking quarks to neutrinos: Flavour mixing:
quarks: Cabibbo-Kobayashi-Maskawa (CKM) matrix
leptons: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

Consider SU(5) multiplets:

$$\mathbf{\overline{5}_1} = \begin{pmatrix} d_R^c \\ d_R^c \\ d_R^c \\ e_L \\ -\nu_e \end{pmatrix}, \qquad \mathbf{\overline{5}_2} = \begin{pmatrix} s_R^c \\ s_R^c \\ s_R^c \\ \mu_L \\ -\nu_\mu \end{pmatrix}, \qquad \mathbf{\overline{5}_3} = \begin{pmatrix} b_R^c \\ b_R^c \\ b_R^c \\ \tau_L \\ -\nu_\tau \end{pmatrix}.$$

If the observed large atmospheric neutrino mixing angle stems from a rotation of $\mathbf{\overline{5}_2}$ and $\mathbf{\overline{5}_3}$, it will induce a large $\tilde{b}_R - \tilde{s}_R$-mixing (Moroi).

$\Rightarrow$ new b_R–s_R transitions from gluino–squark loops possible.

Chang-Masiero-Murayama model

Symmetry breaking chain:

$\mathrm{SO}(10) \to \mathrm{SU}(5) \to \mathrm{SU}(3) \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$.

1. The SUSY-breaking terms are universal at the Planck scale.

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1. The SUSY-breaking terms are universal at the Planck scale.
2. Renormalization effects from the top-Yukawa coupling destroy the universality at M_{GUT}.
3. Rotating $\overline{\mathbf{5}}_2$ and $\overline{\mathbf{5}}_3$ into mass eigenstates generates a $\tilde{b}_R - \tilde{s}_R$ element in the mass matrix of right-handed squarks.

Phenomenological effect: leads to MSSM with

1. new loop-induced $b_R \to s_R$ and $b_L \to s_R$ transitions, while all other FCNC transitions are CKM-like,

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2. all MSSM masses and couplings fixed in terms of a few GUT parameters.

$\Rightarrow$ well-motivated falsifiable version of the MSSM without minimal flavour violation (MFV),
puts largest effects into $b_R \to s_R$, where Standard Model leaves the most room for new physics.

SO(10) superpotential:

$$W_Y = \frac{1}{2} 16_i \, Y_u^{ij} \, 16_j \, 10_H + \frac{1}{2} 16_i \, Y_d^{ij} \, 16_j \, \frac{45_H \, 10'_H}{M_{\mathrm{Pl}}} + \frac{1}{2} 16_i \, Y_N^{ij} \, 16_j \, \frac{\overline{16}_H \overline{16}_H}{M_{\mathrm{Pl}}}$$

with the Planck mass M_{Pl} and

16_i:	one matter superfield per generation, $i = 1, 2, 3$,
10_H:	Higgs superfield containing MSSM Higgs superfield H_u,
$10'_H$:	Higgs superfield containing MSSM superfield H_u,
45_H:	Higgs superfield in adjoint representation,
$\overline{16}_H$:	Higgs superfield in spinor representation.

"Most minimal flavor violation"

The Yukawa matrices Y_u and Y_N are always symmetric. In the CMM model they are assumed to be simultaneously diagonalisable at the scale $Q = M_{\rm Pl}$, where the soft SUSY-breaking terms are universal.
All flavour violation stems from Y_d:

$$\mathsf{Y}_d = V^*_{\rm CKM} \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix} U_{\rm PMNS}$$

For flavour physics relevant: large top-Yukawa coupling in Y_u.
In a basis with diagonal Y_u the low-energy mass matrix for the right-handed down squarks reads:

$$\mathsf{m}^2_{\tilde{d}}\,(M_Z) = \mathrm{diag}\,\left(m^2_{\tilde{d}},\, m^2_{\tilde{d}},\, m^2_{\tilde{d}} - \Delta_{\tilde{d}}\right).$$

with a calculable real parameter $\Delta_{\tilde{d}}$.
Rotating Y_d to diagonal form puts the large atmospheric neutrino mixing angle into $\mathsf{m}^2_{\tilde{d}}$:

$$U^\dagger_{\rm PMNS}\,\mathsf{m}^2_{\tilde{d}}\,U_{\rm PMNS} = \begin{pmatrix} m^2_{\tilde{d}} & 0 & 0 \\ 0 & m^2_{\tilde{d}} - \frac{1}{2}\,\Delta_{\tilde{d}} & -\frac{1}{2}\,\Delta_{\tilde{d}}\,e^{i\xi} \\ 0 & -\frac{1}{2}\,\Delta_{\tilde{d}}\,e^{-i\xi} & m^2_{\tilde{d}} - \frac{1}{2}\,\Delta_{\tilde{d}} \end{pmatrix}$$

The CP phase ξ affects $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing!

Realistic GUTs involve further dimension-5 Yukawa terms to fix the Yukawa unification in the first two generations. One can use these terms to shuffle a part of the effect from $b_R \to s_R$ into $b_R \to d_R$ transitions. A strong constraint on this extra mixing angle is implied by ϵ_K.

Trine,Wiesenfeldt,Westhoff 2009

Phenomenology

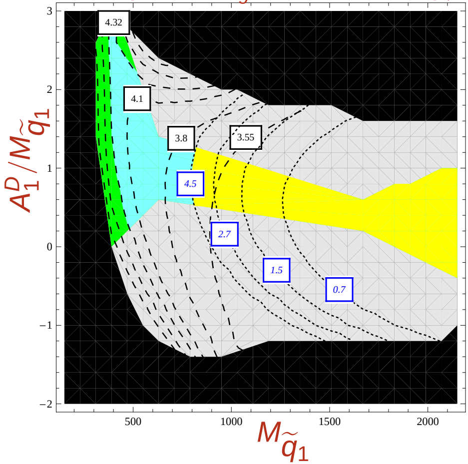
We have considered $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing, $b \to s\gamma$, $\tau \to \mu\gamma$, vacuum stability bounds, lower bounds on sparticle masses and the mass of the lightest Higgs boson.
The analysis involves 7 parameters in addition to those of the Standard Model.

Generic results: Largest effect in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing
tension with $M_h \geq 114\,\mathrm{GeV}$

Collaborators:

Sebastian Jäger, Markus Knopf, Waldemar Martens, Christian Scherrer and Sören Wiesenfeldt

Contour plot for $M_{\tilde{g}} = 350\,\text{GeV}$, $\arg\mu = 0$:



Black: negative soft masses^2
Green: excluded by $\tau \to \mu\gamma$ and $b \to s\gamma$
Blue: excluded by $\tau \to \mu\gamma$
Gray: excluded by $B_s - \overline{B}_s$ mixing
Yellow: allowed

dashed lines: $10^4 \cdot Br(b \to s\gamma)$; dotted lines: $10^8 \cdot Br(\tau \to \mu\gamma)$.

Conclusions

- The DØ result for the dimuon asymmetry in B_s decays supports the hints for $\phi_s < 0$ seen in $B_s \to J/\psi\phi$ data. The central value is easier to accomodate if both a_{fs}^s and a_{fs}^d receive negative contributions from new physics.

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- Large CP-violating contributions to $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing are possible in supersymmetry without violating constraints from other FCNC processes.

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- A global fit to the UT indeed shows a slight preference for a new CP phase $\phi^\Delta_d < 0$, driven by $B(B^+ \to \tau^+\nu_\tau)$ (and possibly ϵ_K).
- Large CP-violating contributions to $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing are possible in supersymmetry without violating constraints from other FCNC processes.
- A study in the CMM model of GUT flavour physics has revealed a possible large impact of the atmospheric mixing angle on $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing without conflicting with $b \to s\gamma$ and $\tau \to \mu\gamma$.